

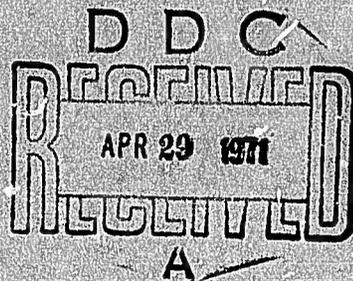
PAPER P-713

ADVANCES IN LASER-PUMPING TECHNOLOGY

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John F. Asmus

December 1970



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**INSTITUTE FOR DEFENSE ANALYSES
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ABSTRACT

The early years of laser research were characterized by a search for new active media and new transitions. Although progress is continuing in these areas, much of the emphasis has shifted to the advancement of pumping technology. To a considerable extent this shift in emphasis reflects a maturing process taking place in the laser field in response to a fuller understanding of real and potential laser applications. This paper* discusses the manner in which pumping technology has evolved and expanded in moving toward higher laser performance and the realization of a broader range of applications. Foremost among these developments are chemical and gas-dynamic excitation in gases, sensitization and spectral matching in optically pumped solids, face-pumped disc technology, and high-pressure discharge excitation. Also described is the manner in which these and other techniques have emerged to advance the state of the art in peak power, average power, efficiency, or other performance parameters. No attempt is made to include intermediate pumping methods involving laser pumped lasers or nonlinear optics.

*This is a reprint of an invited paper presented at the Fall Meeting of the Optical Society of America, September 29 - October 2, 1970 in Hollywood, Florida.

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I. INTRODUCTION

The early years of laser research were characterized by a search for new active media and new transitions. This exploratory phase produced hundreds of distinct lasers and well over one thousand individual primary lines. Although new laser transitions continue to emerge, the discovery rate has decreased perceptibly in recent years. An example of this trend is illustrated in Figure 1 where the numbers of new semiconductor materials reported in U.S. literature as exhibiting laser emission are indicated for each year. The volume of U.S. literature pertaining to semiconductor lasers is also shown in Figure 1. It can be seen that whereas the level of activity (as measured by numbers of publications) has dropped off in recent years, the rate of discovery of new lasers has decreased much faster. Similar trends appear for most categories of lasers (viz., optically pumped solid-state lasers, dye lasers, gas discharge lasers, and molecular lasers).

There are diverse reasons for this downward trend in the discovery of new laser media. Examples are a reduced level of defense R&D spending and an exhaustion of the more obvious or convenient candidate laser materials. However, a major contributing factor is a shift from discovery-oriented to goal-oriented R&D, as to be expected when a novel technology begins to mature. As a fuller understanding of the real and potential laser applications has emerged, the emphasis has shifted from the development of new lasers to the achievement of higher performance. Higher performance refers to higher peak power, higher average power, higher brightness, higher efficiency, reduced size and weight, or some combination of these.

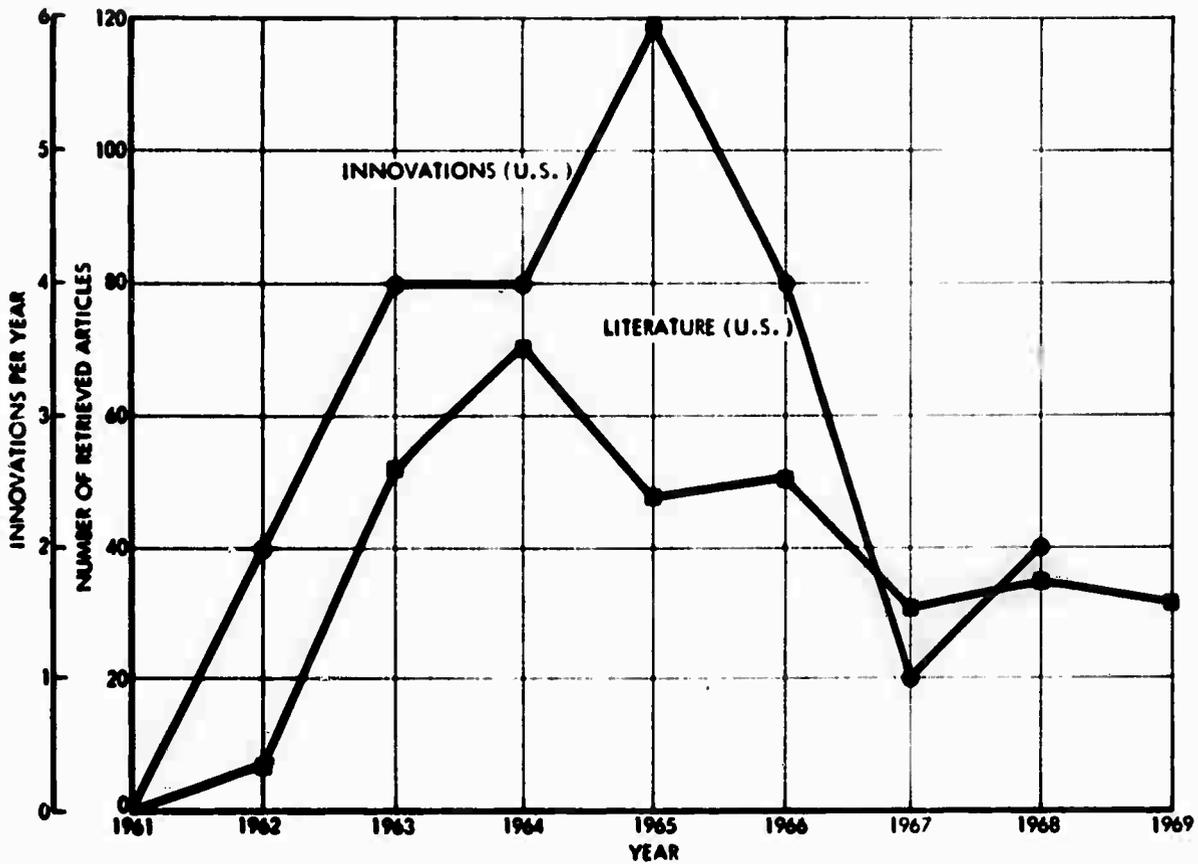


FIGURE 1. New Materials For Semiconductor Lasers

The subject of this paper concerns one of the more fruitful avenues to improved performance, namely, the development and advancement of new and modified pumping techniques. In gaseous and solid-state lasers quite different approaches are being pursued. Discussions of the more recent of the significant advances in laser-pumping technology follow.

II. OPTICALLY PUMPED SOLID-STATE LASERS

Through their ability to efficiently store energy, optically pumped solid-state lasers find broad application where high peak power is required. CTR plasma generation and portable rangefinders are examples of situations where performance requirements are stimulating advances in laser-pumping technologies. In plasma generation the need for substantial increases in pulse power and energy has fostered serious development of face-pumped disc systems. Quite different from this are requirements for efficiency and weight that have led to major advances in spectrally matched and sensitized pumping.

A. THE DESIGN OF FACE-PUMPED DISC SYSTEMS

At the present time Nd:glass is the only solid laser material suitable for the generation of short pulses (10^{-11} - 10^{-8} sec) containing upwards of a thousand joules. Unfortunately, beam fluxes exceeding 20-40 joules/cm² generally produce glass damage and a deterioration of the medium. Consequently, higher energy systems require output apertures of hundreds or thousands of square centimeters.

The face-pumped disc laser has been under investigation for several years⁽¹⁾ as a means of attaining a large aperture configuration with uniform pumping and minimal thermal distortion. In open configurations of this sort (Figure 2), one of the most serious problems has been that of devising an efficient coupling between flash tubes and discs. This is necessary in order to remain below the explosion limit for xenon flash tubes. Thus, overall system design optimization is exceedingly critical.

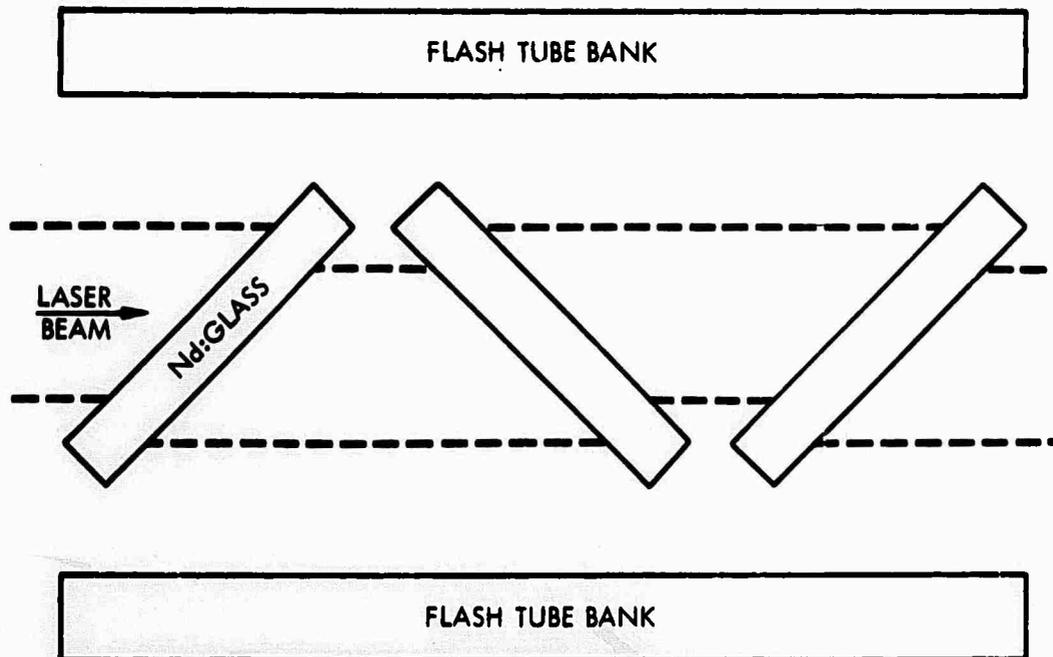


FIGURE 2. Large-Aperture Face-Pumped Laser

Recently, the work of Swain et al.⁽²⁾ has led to several hundred joules per pulse performance, thereby approaching the leading solid rod systems. This is in itself something of a breakthrough in that effective face pumping has been demonstrated. However, from a long-range point of view the most significant recent advance is the development of the NRL laser optimization code⁽³⁾. This code is in reality three codes. The first is the Laser Amplifier/Oscillator Design Code that computes the laser output, given initial conditions such as geometry, input signal, and inversion. The second sub-code is the Pump Source Optimization Code that generates the detailed output spectrum of a xenon lamp in terms of the electrical input and reabsorbed radiation. Third is the Three-D Cavity Transfer Efficiency Code that couples the flash lamp(s) to the active media. Together these sub-codes permit the parametric optimization of highly complex (or simple) laser systems.

Initial investigations with the code indicate that laser performance is a sensitive function of several design parameters in large face-pumped systems. Figure 3 shows an example of the relationship between the optimum pulse duration and input energy. Thus, it is reasonable to assume that substantial advances may emerge through design optimization of large systems. The design of a one kilojoule face-pumped disc array is presently under way.

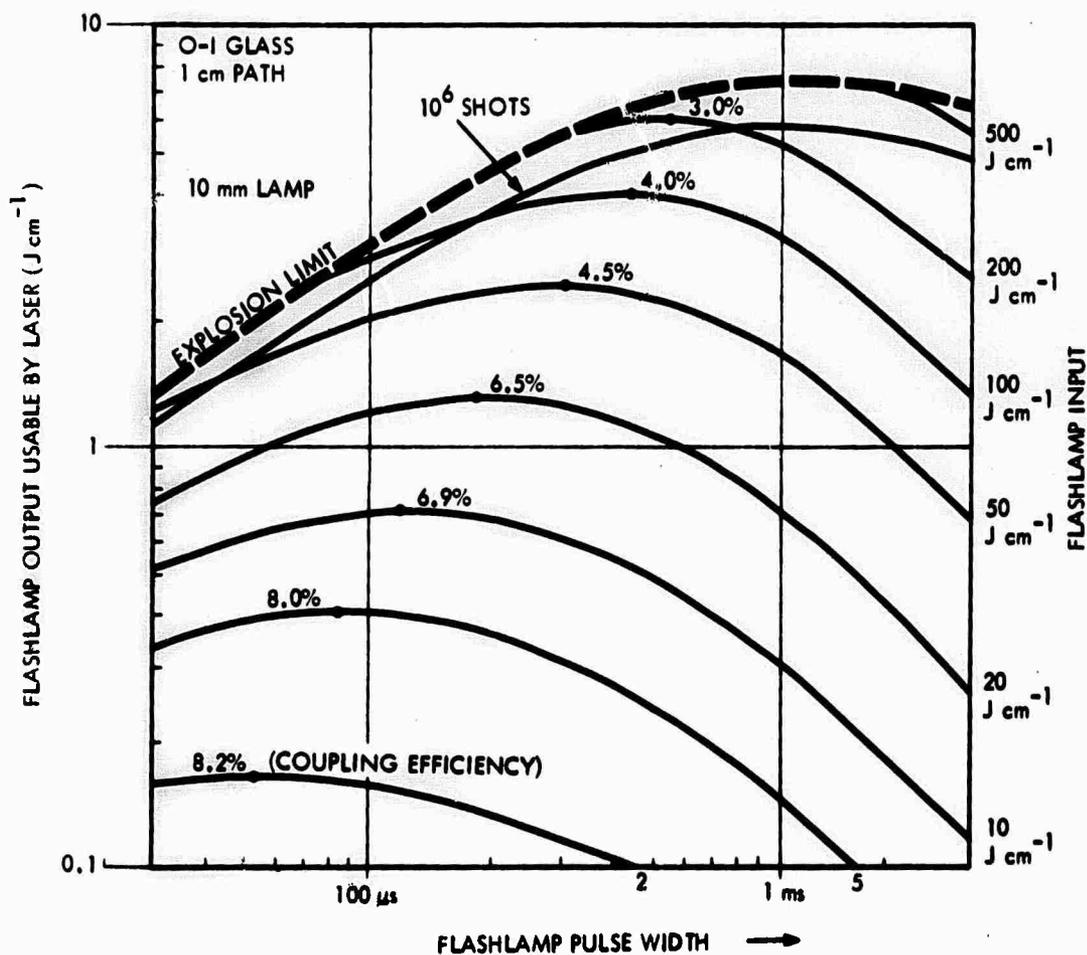


FIGURE 3. Flash Tube Pumping Optimization (Xenon - Nd:Glass)
 (For a contour of constant flashlamp input and a particular pulse width, the output usable by laser is read from the ordinate at left.)

B. SPECTRALLY MATCHED LASER PUMPING

At the opposite end of the optically pumped laser spectrum from the plasma generation device is the lightweight portable or flyable laser. These typically employ Nd:YAG which because of a rather high gain ($0.85 \text{ cm}^{-1}/\text{J}/\text{cm}^3$) have a low threshold that facilitates a high overall efficiency. This is quite desirable for portable range-finders for instance.

One of the principal difficulties associated with Nd:YAG is shown in Figure 4. Here it can be seen that the pump absorption bands of the neodymium ion in YAG are quite narrow in relationship to the blackbody spectrum approximated by a tungsten or xenon lamp.

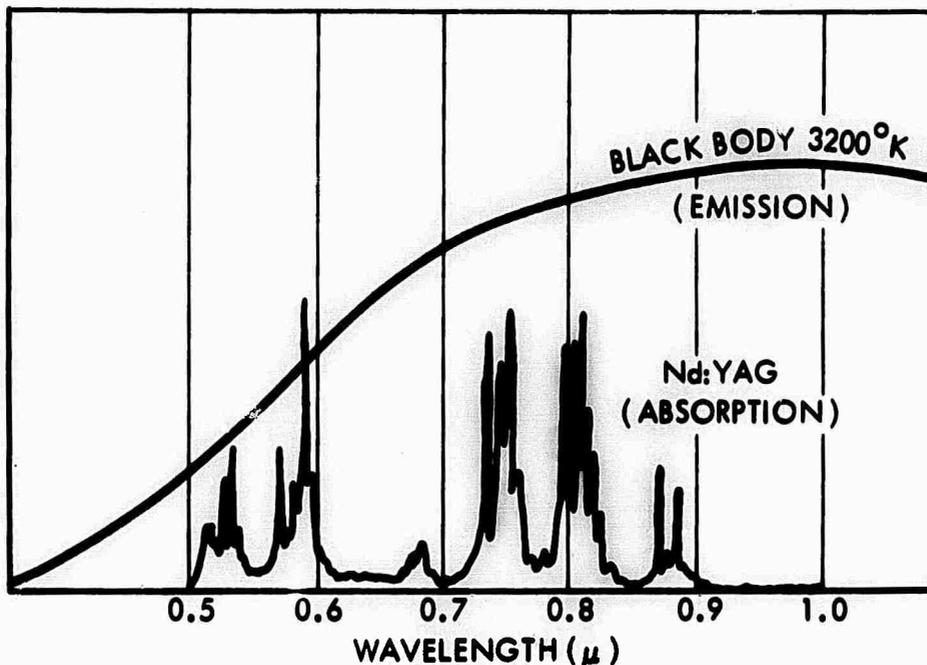


FIGURE 4. Nd:YAG Pump Bands And Blackbody Distribution

Some improvement in Nd:YAG laser efficiency is possible by krypton lamp pumping as some of the residual broadened line structure overlaps the neodymium absorption lines. Figure 5 shows the input-output characteristics of a particular Nd:YAG laser where the improved spectral match of the krypton lamp is evident.

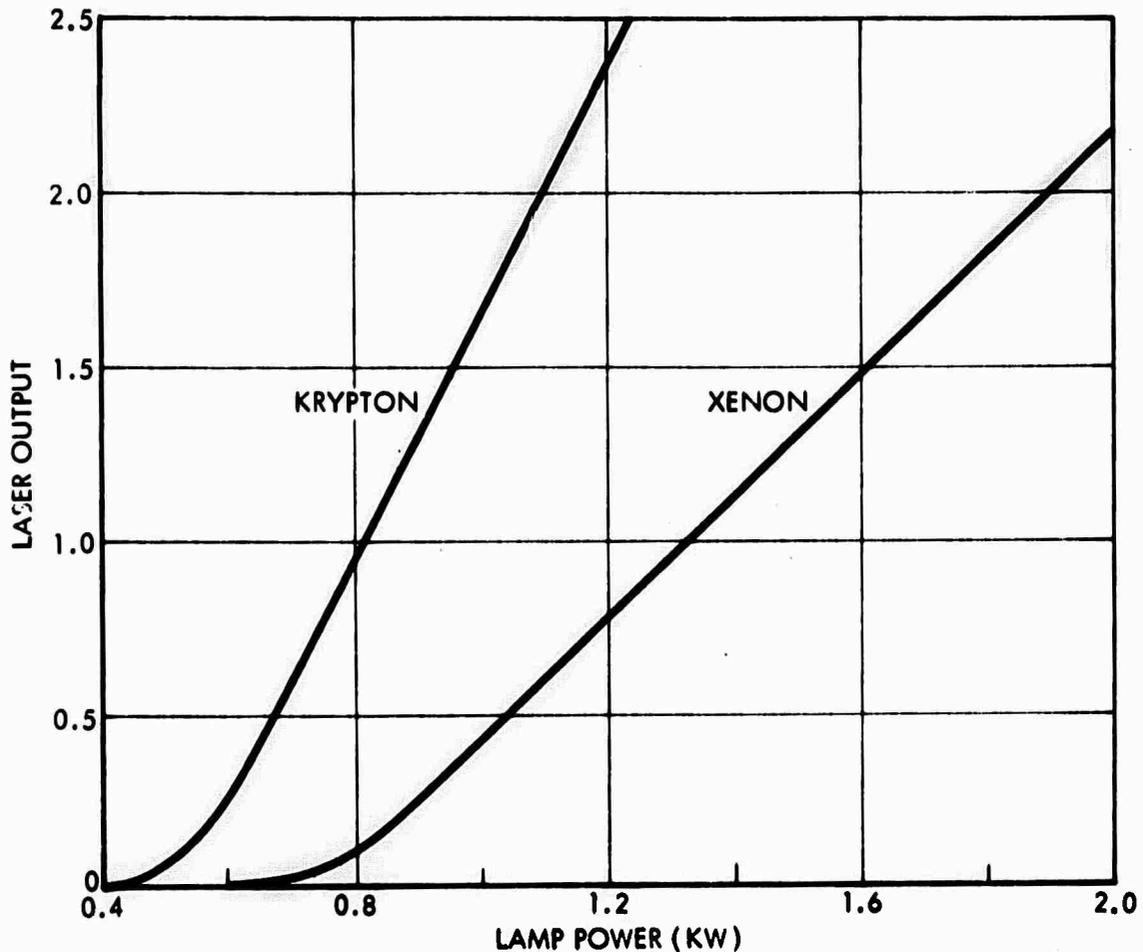


FIGURE 5. Comparison of Krypton and Xenon Pumping of Nd:YAG

The recent results of Liberman et al.⁽⁴⁾ utilizing self-reversed line radiation from a K-Hg lamp are rather dramatic. The good spectral match between this lamp and Nd:YAG is shown in Figure 6. If one convolves the emission spectra of various lamps with the Nd:YAG absorption curve, the pumping efficiencies appearing in Figure 7 result. It can be seen that the K-Hg lamp represents a substantial potential improvement in pumping efficiency over the other types. The presently realized performances of these pump lamps are also given in the figure.

The efficiency values given in Figure 7 do not give the whole story, however. Tungsten lamps cannot reach power levels in excess

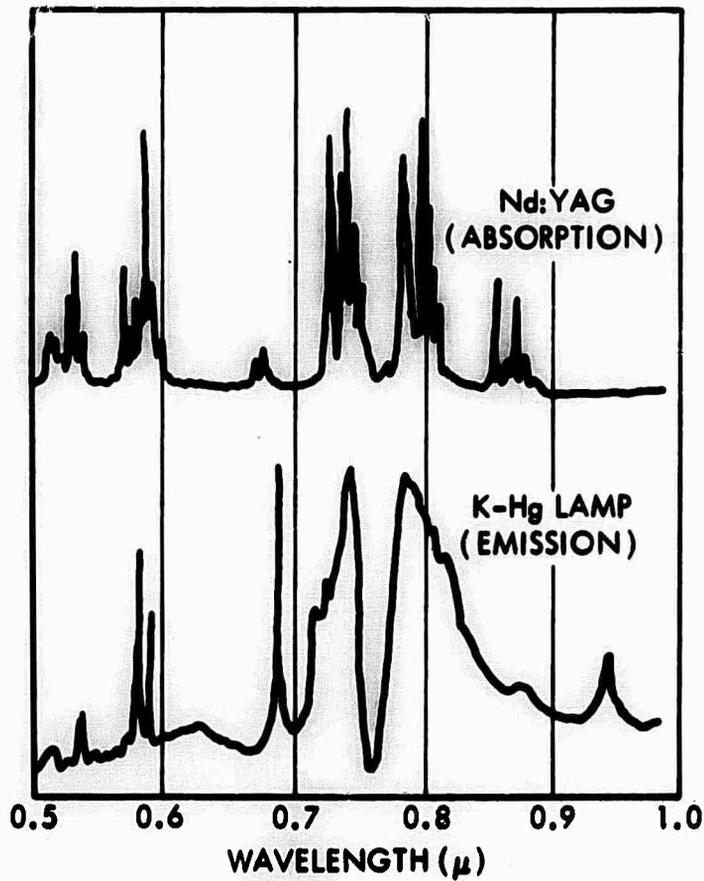


FIGURE 6. Spectral Match Between Nd:YAG Pump Bands and K-Hg

	TUNGSTEN 3200°K	KRYPTON (CW)	K-Hg (CW)
PREDICTED SLOPE EFFICIENCY	3.9%	4.0%	8.9%
OBSERVED OVERALL EFFICIENCY	1.3%	2.5%	2.4%

FIGURE 7. Effect of Spectral Matching on Nd:YAG Laser Efficiency

of about 500 watts per linear cm. Therefore the discharge lamps are able to work further above threshold. Unfortunately, the K-Hg lamp must run at about 700°C so that there remain material and seal problems to be solved before its usage becomes widespread. Also, it is turning out that K-Rb is superior to K-Hg for spectral matching and present developmental emphasis is centering on this mixture.

Finally, luminescent GaAsP dome diodes have been used to spectrally pump CW YAG lasers⁽⁵⁾. However, application may be limited to long-lived spaceborne lasers until higher powers are available from diode sources.

C. PUMPING VIA SENSITIZATION

The previous method of improving the efficiency of optically pumped lasers involved modifying the pump spectrum to match the narrow absorption bands of the active ion. However, as lamps tend toward a blackbody spectrum when driven hard, it is in principle more tempting to broaden the active ion absorption bands to match more conventional lamps. This is especially true since xenon lamps can have a very high radiant efficiency in the visible.

Early attempts to sensitize Nd with Cr in crystalline hosts appeared promising.^(6,7) The energy transfer scheme for these ions is shown in Figure 8 for Nd,Cr:YAG. Disappointingly, the factor-of-two reduction in threshold to be expected through Cr sensitization does not appear to be generally realized in practice. This is a consequence of a deterioration in the optical quality of YAG with additional doping, and further complicated by a reduction in thermal conductivity.

However, in the last year or two, ions which are considerably more deficient in pump bands than Nd have shown major performance advances through sensitization. Foremost among these are the Er and Ho ions which emit near 1.5 μ and 2.1 μ , respectively.

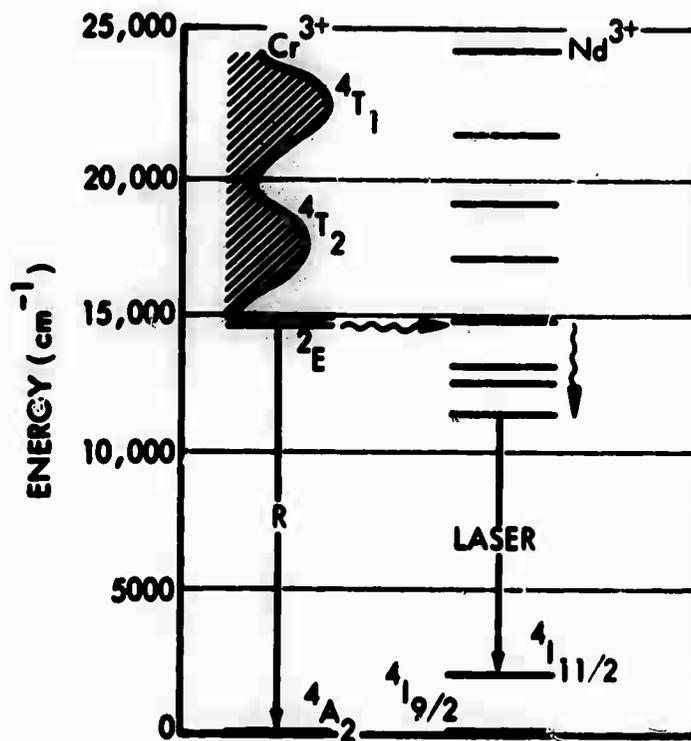


FIGURE 8. Energy Transfer in Nd,Cr:YAG

Recently, Thornton et al.⁽⁸⁾ have studied the optimization of Er:YAG and Er:glass lasers sensitized with Yb, Ce, Nd, and Eu. With Er(2%), Yb(5%):YAG, a threshold as low as 55 joules was obtained. Owens Illinois type Ed-7 · Er,Yb:glass exhibited a threshold of 68 joules under similar circumstances. However, the slope efficiency for Ed-7 appears somewhat higher than for YAG especially in repetitive pulse operation. At 1 pps, Q-switched outputs of 40 mj were obtained at 140 joules input. For repetitive Q-switch operation the efficiency of 0.03% is certainly competitive with many laser types. Further, Woodcock et al.⁽⁹⁾ have developed an Nd,Yb:glass cladding which circumvents Nd depopulation of the Er so that improvements in efficiency of about fivefold may be possible.

An equally spectacular advance has taken place with Ho lasers. Formerly, holmium at 2.1μ was of marginal usefulness as reasonable thresholds could only be obtained at cryogenic temperatures due to the small ground state splitting. However, recently Remski and Smith⁽¹⁰⁾ have reported a factor of 20 decrease in the room temperature threshold of Ho:YAG when sensitized with Er and Tm. The value reported was 60 joules for a $150\mu\text{s}$ pump pulse.

In itself a threshold value does not characterize the performance of such lasers. However, the fact that thresholds commensurate with man-portable energy sources (e.g., batteries) have been obtained at room temperature opens the way to field utilization (e.g., range-finders).

III. GAS LASERS

The development of the N_2 - CO_2 -He gas discharge laser about five years ago heralded the era of the high-power molecular laser. Materials processing (cutting, trimming, welding, etc.) and material interaction studies have fueled the need for increasingly more powerful molecular lasers. The flowing axial discharge CO_2 laser very quickly reached its practical limit of about one kilowatt CW. This technology continues to advance in power through developments in fast flow and transverse discharge technologies.

However, the major emphasis in the R&D aimed at significantly higher powers has centered on new volumetric pumping mechanisms. Two of the most advanced of these are gas-dynamic and chemical excitation.

A. CHEMICAL REACTION PUMPED LASERS

The traditional molecular laser functions by virtue of enhanced vibrational excitation of an upper level augmented by enhanced deactivation of a terminal level. Rapid rotational equilibration often plays a crucial role in the achievement of a partial inversion at low temperatures in cooperation with the above processes.

Such conditions have been achieved within various experimental scenarios. However, recent developments in direct chemical excitation have fostered considerable interest in this process. Chemical vibrational excitation itself was first observed by Kasper and Pimentel as early as 1965⁽¹¹⁾ by means of flash photolysis. In 1968 Gross et al.⁽¹²⁾ reported a chain HF reaction version of this excitation process involving a mixture of F_2O and H_2 . The photolytic initiation step is given by



where the photon is supplied by a xenon flash tube. The reaction products can then react with the molecular hydrogen by the reactions



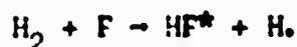
The atomic hydrogen can react further to propagate the chain.



As (2), (4), and (5) are exothermic reactions, energetically the molecule HF can be formed in an excited state. Consequently, in such a chemical system a total inversion is possible if the reaction goes sufficiently fast (relative to thermalization). Unfortunately, in such flash photolysis lasers the flash lamp input generally exceeded the laser output by a considerable margin.

Four recent developments in the excitation of chemical lasers conspire to transform these devices from laboratory curiosities into practical systems. These are (1) the achievement of CW radiation from a dilute supersonic flow, (2) purely chemical production of free fluorine atoms in mixing systems, (3) vibrational transfer excitation of CO_2 by excited DF, and (4) uniform volumetric electron beam excitation of HF reactions. These are discussed below.

The achievement of CW laser radiation from HF in a dilute supersonic flow was reported by Spencer et al.⁽¹³⁾ in 1969. In this system a mixture of N_2 and SF_6 is heated to $2000^{\circ}K$ in an arc heater to produce free fluorine. This mixture is allowed to expand through a supersonic nozzle where mixing with H_2 takes place leading to the reaction (see Figure 9)



Two important elements contributed to the success of this experiment. First, was the supersonic flow velocity which both spatially extended the reaction zone so that it could be made to coincide with an optical resonator and retarded F atom recombination. Second, was the heavy dilution which prevented an excessive temperature rise in the flow. Thus, a low rotational temperature pervaded the reaction zone facilitating a partial inversion and unmodified deactivation rates.

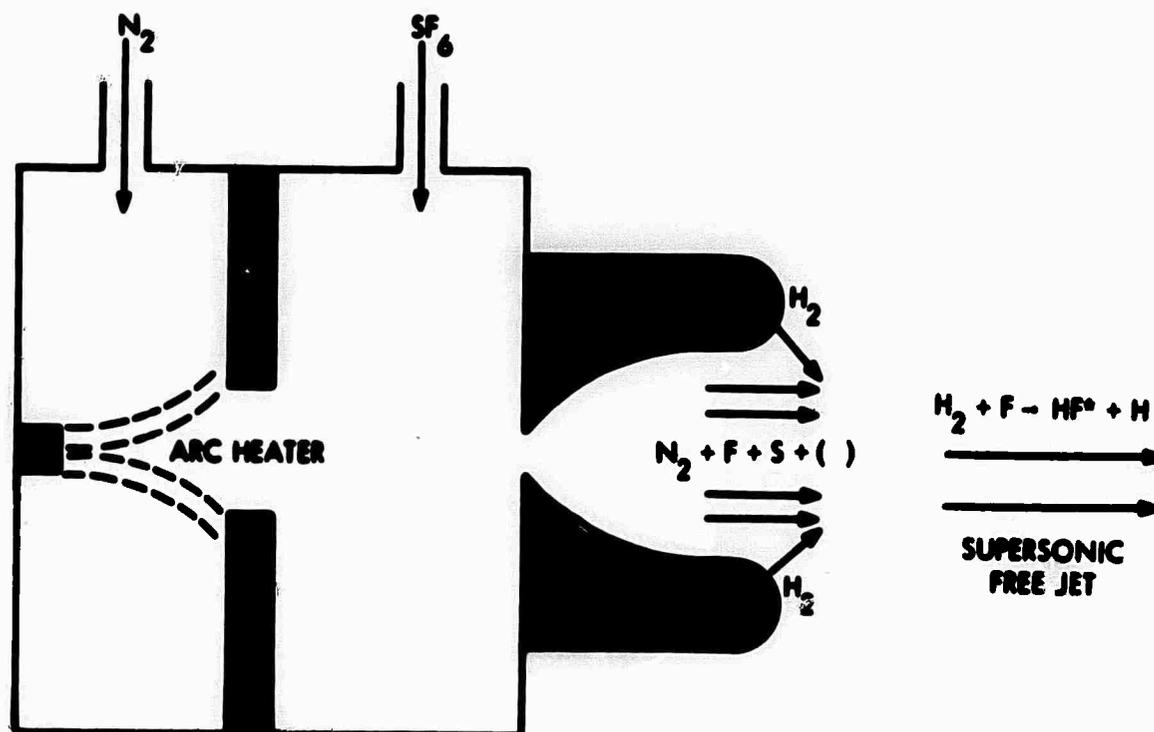


FIGURE 9. Segment of Supersonic CW Chemical Laser

The second development was the production of atomic fluorine by purely chemical means. Cool⁽¹⁴⁾ achieved this by mixing NO and F₂ in a dilute flowing system. This step eliminated the need for either flash photolysis or arc heater initiation of HF reactions. Coupled with this work was the next major development, which involved the observation that HF or DF vibrational energy couples efficiently to CO₂ vibrational excitation. Vibrational transfer from DF to CO₂ can be quite beneficial in that the molecular excitation can be stored by the metastable 00⁰1 level of CO₂ thereby lessening the effects of deactivation. DF is more favorable than HF for this purpose, possibly due to a better resonance with CO₂.

A potentially important advance in chemical laser excitation involves uniform volumetric initiation by means of high-energy electrons. This technique holds promise for the production of high-power pulses via chemical reactions. The need for uniform initiation stems from the fact that if a localized reaction zone propagates through a closed chamber, a heterogeneous time-varying mixture of emitting and absorbing regions will develop. In addition to the difficulty in efficiently extracting energy from a heterogeneous system is the further disadvantage that the temperature and pressure rises within the chamber shift the reaction kinetics away from optimum excitation. Gregg et al.⁽¹⁵⁾ have ignited mixtures of N₂F₄-H₂ and NF₃-H₂ with 1.2-Mev electrons delivered during a 50-nsec pulse. Experiments at a total pressure of 100 torr resulted in stimulated emission from six vibrational-rotational lines of HF for durations of approximately 150 nsec.

B. THERMALLY PUMPED MOLECULAR LASERS

Several authors have proposed thermal excitation of molecular lasers. Among the earliest of these were Basov and Oraevskii⁽¹⁶⁾ (1963), Hurle and Hertzberg⁽¹⁷⁾ (1964), Wells⁽¹⁸⁾ (1965), and Shimoda⁽¹⁹⁾ (1965). The experimental results reported by Gerry⁽²⁰⁾ with regard to the generation of 60 kw from a thermally excited gas-dynamic laser suggest a considerable potential for this type of pumping.

In contrast to chemical lasers, thermal excitation is unselective. Consequently, by raising a gas mixture to a high equilibrium temperature, one populates excited vibrational-rotational levels without producing an inversion. Gerry's technique utilizes rapid expansion of the heated gases through a supersonic nozzle to generate the non-equilibrium conditions leading to an inversion. The following sequence traces the functional operation of such a device.

Initially, a mixture of N_2 , CO_2 and a catalyst⁽²¹⁾ such as H_2O or He is elevated in temperature to thermally populate excited vibrational-rotational levels. This excited gas is then allowed to expand rapidly through a supersonic nozzle. The relaxation times for internal translational and rotational excitations are quite fast and it is this energy that supplies the directed flow kinetic energy. However, the vibrational relaxation time is long compared to expansion duration so that the supersonic flow emerging from the nozzle has a nonequilibrium vibrational temperature. According to Herzberg⁽²²⁾ the vibrational-rotational populations before and after expansion can be represented by the distributions given on Figure 10. It is evident from the illustrated P-branch transition that with a sufficiently low rotational temperature following expansion a partial inversion will develop. Basov et al.⁽²³⁾ have calculated this inversion as a function of the initial equilibrium gas temperature in an N_2 - CO_2 system. They find a maximum inversion of

$$\frac{\Delta N}{N_0} = 0.6 \times 10^{-4}$$

for a temperature of 1500°K . Gerry⁽²¹⁾ points out that the inversion can be intensified by enhancing lower level relaxation through the addition of a catalyst. However, an automatic benefit in the gas-dynamic laser (GDL) is the supersonic flow that automatically sweeps spent gas from the nonequilibrium regime. Biryukov et al.⁽²⁴⁾ have calculated the inversion in a supersonic jet at various times in the expansion (Figure 11) and for different gas mixtures as a function of stagnation temperature (Figure 12).

Two of the physical embodiments of the GDL are shown schematically in Figures 13 and 14. The device of Figure 13 has been described by Sobolev⁽²⁵⁾ and employs a shock tube to generate the supersonic flow. Figure 14 illustrates the supersonic mixing laser developed by Bronfin et al.⁽²⁶⁾ In this device thermal excitation is achieved in nitrogen by means of an arc heater. Then vibrational freezing develops during the expansion followed by selective excitation upon the injection of cold CO_2 and a catalyst (He).

C. CW GAS LASER PERFORMANCE

Having discussed several of the recent developments in flowing gas lasers (chemical and gas kinetic), it is perhaps appropriate to compare the present performance of such devices. Various parameters of these as well as the electrically excited flowing CO_2 laser are tabulated in Figure 15. The first and second columns give, respectively, the laser type and its principal active molecule(s). The approximate center wavelength for each laser is given in column three. The theoretical maximum power in the laser transition for each is given in the next column, based on the excitation mechanisms and gas compositions. The remaining entries show actual specific and gross performance figures for leading devices that have been reported (as of October 1970).

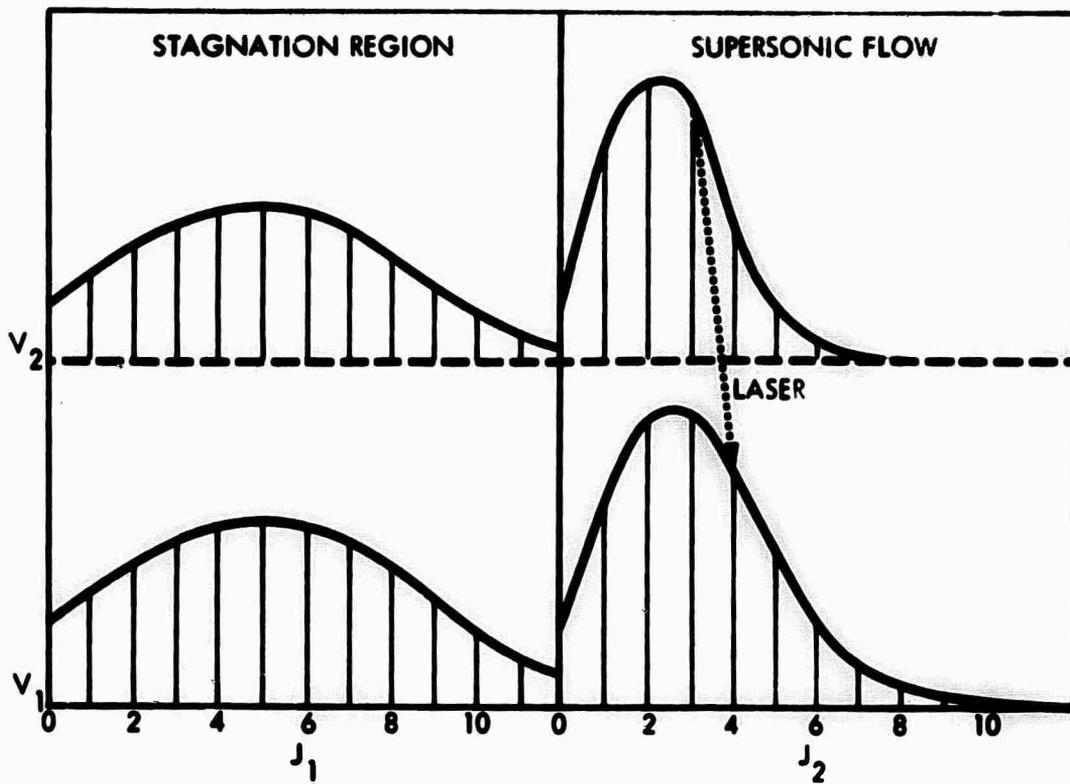


FIGURE 10. Partial Inversion in Supersonic Flow

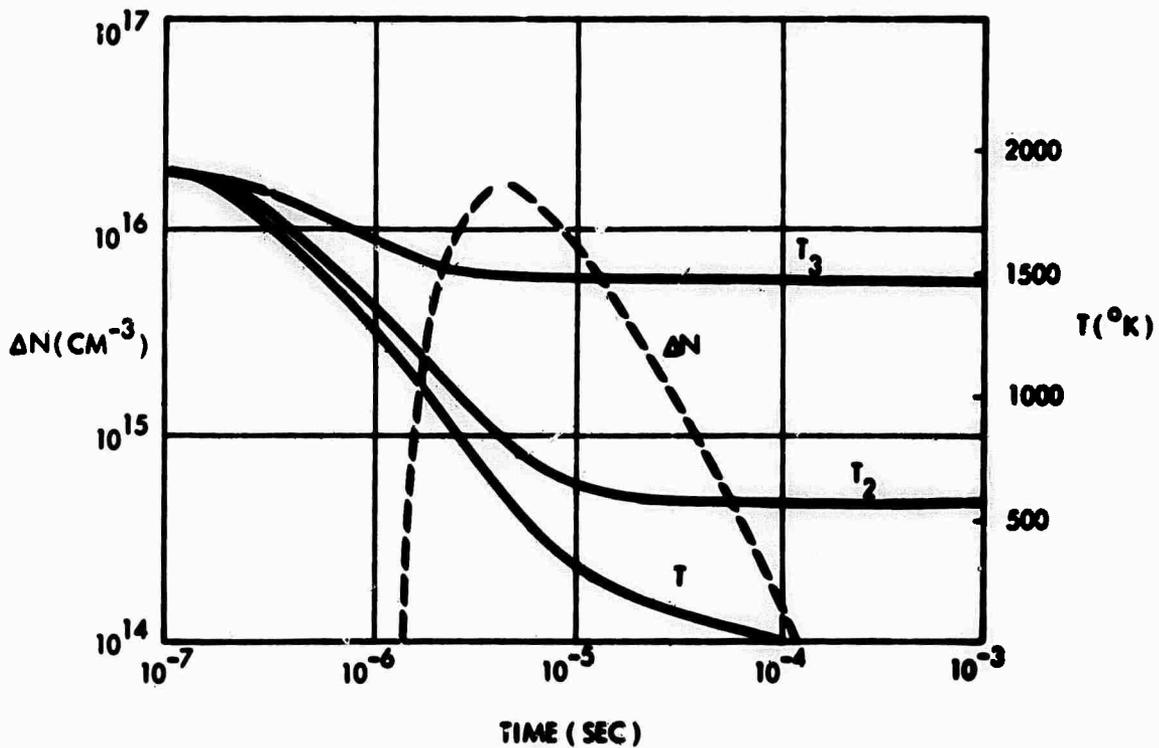


FIGURE 11. Vibrational Freezing In A Supersonic Flow
 $(\text{CO}_2:\text{N}_2 = 1.5, T_0 = 1900 \text{ K}, R_0 = 0.3 \text{ CM})$

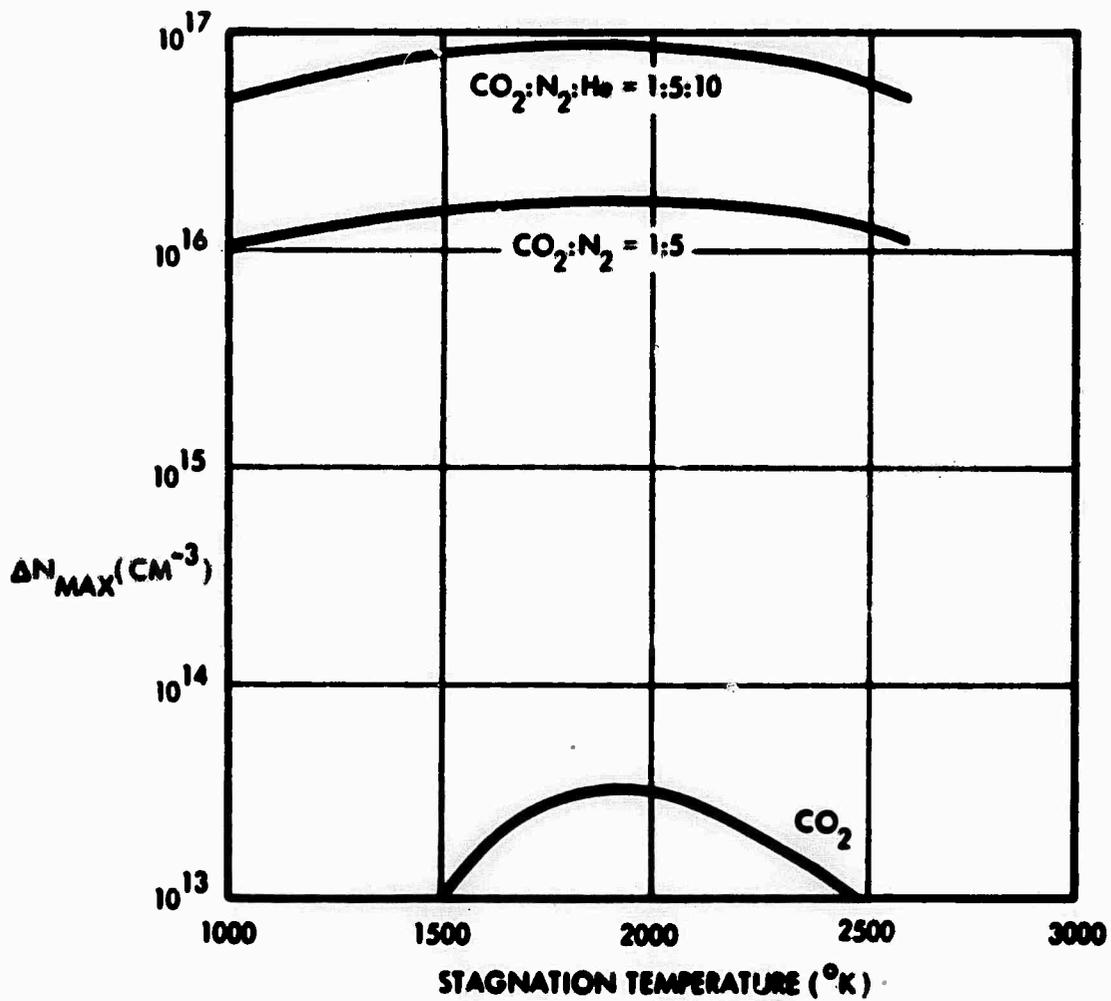


FIGURE 12. Inversion Versus T_0 For Various Mixtures

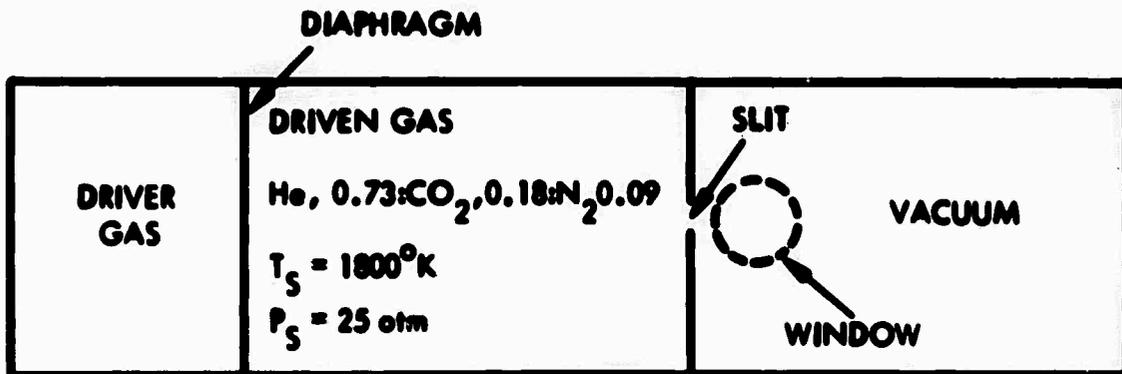


FIGURE 13. Sobolev Shock-Tube GDL

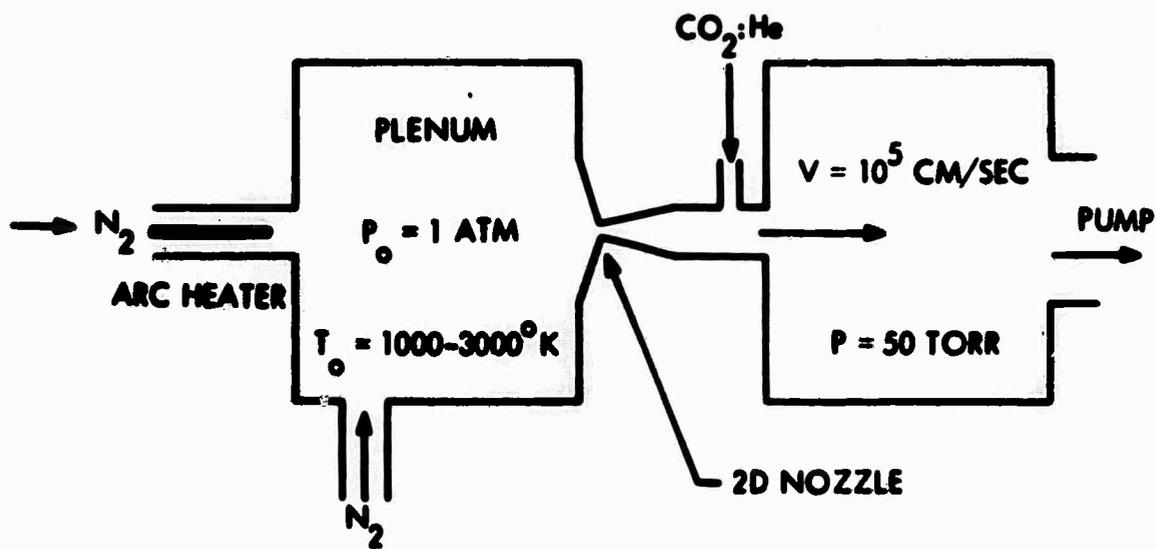


FIGURE 14. Supersonic Thermal Mixing Laser

LASER TYPE	MEDIUM	$\lambda(\mu)$	INTERNAL PWR. (THEOR)	PRESENT PERFORMANCE	
				(SPECIFIC)	(TOTAL)
THERMAL (MIXING) (ODL) ELECTRICAL	$N_2 + CO_2 + \dots$	10.6	25 kw/lb/sec	10 kw/lb/sec**	200 w
			-----	-----	60 kw
			39 kw/lb/sec	32 kw/lb/sec**	18 kw
CHEMICAL ($CS_2 + O$)	$CO + \dots$	5.4	330 kw/lb/sec*	0.2 kw/lb/sec*	70 mw
CHEMICAL (v-v)	$DF + CO_2 + \dots$	10.6	410 kw/lb/sec*	22 kw/lb/sec*	162 w
CHEMICAL (DF, HF)	$DF, HF + \dots$	3.9, 2.7	5 Mw/lb/sec*	100 kw/lb/sec**	1.8 kw

*TYPICAL DILUENT CONCENTRATION
**AT MAXIMUM POWER

FIGURE 15. Chemical and G_{15} Kinetic Laser Performance (CW)

D. HIGH-PRESSURE PULSED GAS LASERS

Substantial performance advances in pulsed gas lasers have been achieved by means of high-voltage and high-pressure electrical discharge technologies. The transverse pin configuration developed by Beaulieu⁽²⁷⁾ has found application not only in exciting atmospheric pressure CO₂, but initiating CO chemical lasers as well. Beaulieu's transversely excited atmospheric (TEA) pressure configuration is shown schematically in Figure 16. This distributed discharge arrangement facilitates the excitation of relatively large volumes at high pressures so that high-energy densities are possible. In order to maintain spatial discharge homogeneity and minimize deactivation effects, the useful pulse length from this device is generally less than μ s for CO₂.

This configuration is also useful in volumetrically initiating pulsed chemical lasers. The pulse performance of several electrical discharge excited chemical and gas lasers is tabulated in Figure 17. It should be noted that the two electrical CO₂ lasers tabulated have attained pulse energies in excess of 100 J; a level previously attainable only with large optically pumped solid-state lasers.

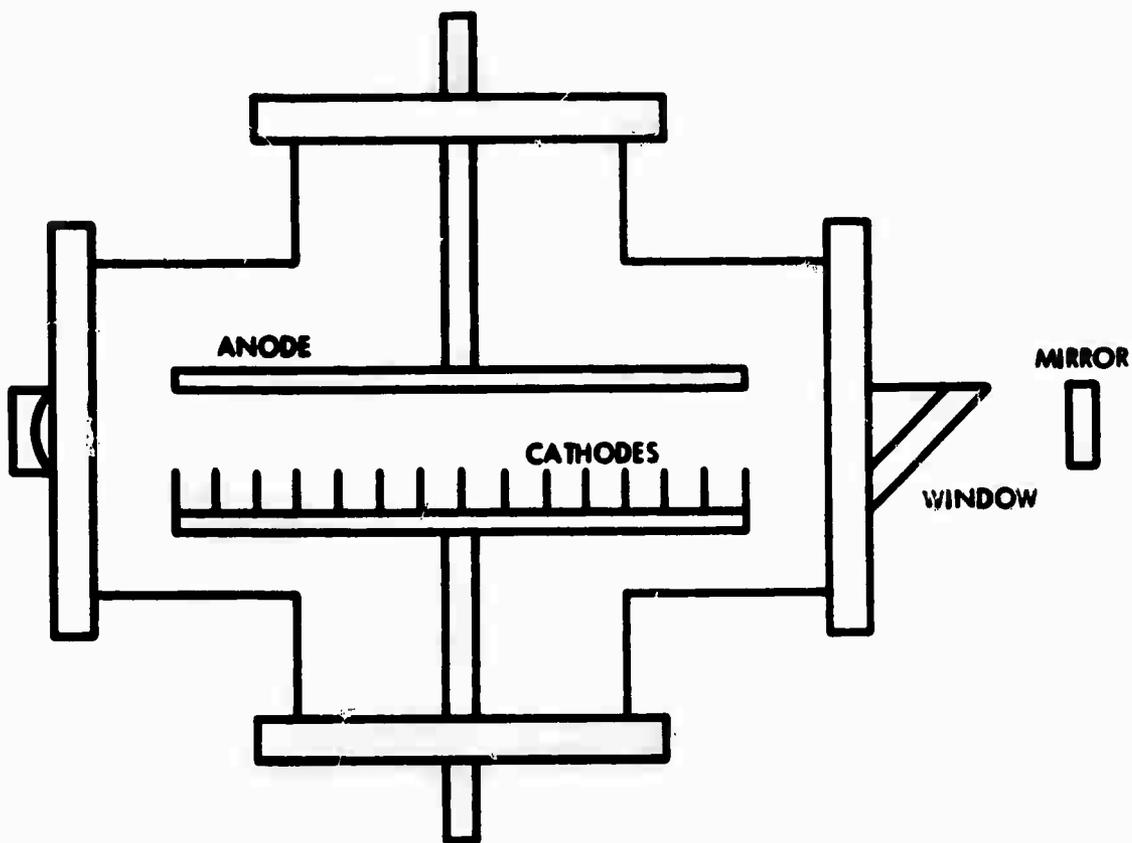


FIGURE 16. Beaulieu TEA Laser (Transversely Excited Atmospheric Pressure)

TYPE	λ (μ)	OUTPUT	EXTRACTION	P
CHEMICAL (HF)	2.7	70 mJ*	0.7 mJ/cc	30 Torr
CHEMICAL (CO)	5.4	30 mJ**	—	< 100 Torr
TEA (CO ₂)	10.6	130 J***	10 mJ/cc	760 Torr
HV-AXIAL (CO ₂)	10.6	170 J	1-3 mJ/cc	~ 40 Torr

*SOVIET
 **CANADIAN
 ***FRENCH

FIGURE 17. Pulsed Chemical and Electrical Laser Performance

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Abstract

The early years of laser research were characterized by a search for new active media and new transitions. Although progress is continuing in these areas, much of the emphasis has shifted to the advancement of pumping technology. To a considerable extent this shift in emphasis reflects a maturing process taking place in the laser field in response to a fuller understanding of real and potential laser applications. This paper discusses the manner in which pumping technology has evolved and expanded in moving toward higher laser performance and the realization of a broader range of applications. Foremost among these developments are chemical and gas-dynamic excitation in gases, sensitization and spectral matching in optically pumped solids, face-pumped disc technology, and high-pressure discharge excitation. Also described is the manner in which these and other techniques have emerged to advance the state of the art in peak power, average power, efficiency, or other performance parameters. No attempt is made to include intermediate pumping methods involving laser pumped lasers or nonlinear optics.

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Laser pumping
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